ARKIV FÖR FYSIK Band 15 nr 36

Communicated 8 April 1959 by MANNE SIEGBAHN and ERIK HULTHÉN

The 225-cm cyclotron at the Nobel Institute of Physics, Stockholm

By H. ATTERLING and G. LINDSTRÖM[1]

With 14 figures in the text

ABSTRACT

A description is given of the 225-cm fixed-frequency cyclotron at the Nobel Institute of Physics in Stockholm. This cyclotron has operated reliably and stably for several years producing internal beams of protons, deuterons, alpha particles and heavy ions. The nominal energy attained at a radius of 90 cm with the present oscillator frequency is about 11 MeV per nucleon. So far, internal deuteron beam currents up to approximately 300 μA at a nominal energy of about 22 MeV have been normal.

An unusual feature possessed by this cyclotron is the dee biasing system based on the use of condensers as electrical terminations of the dee stems.

1. Introduction

In two papers [1, 2] published several years ago the initial performance of the fixed-frequency 225-cm cyclotron at the Nobel Institute of Physics in Stockholm was reported. The present paper gives a more detailed description of the machine. In the following specification some characteristic data are given.

Magnet pole face diameter	225 cm
Smallest diameter of tapered pole tips	211 cm
Maximum magnetic induction	about 20 kilogauss
Magnetic induction used for deuteron acceleration at present oscillator frequency	10.7 kilogauss
Dee radius	95 cm
Present oscillator frequency	8.1 Mc/sec
Nominal particle energy at a radius of 90 cm (nominal exit radius)	about 11 MeV/nucleon

In principle, the 225-cm cyclotron has many of the fundamental design features of the Crocker 60-inch cyclotron [3] of the University of California at Berkeley. Thus, each of the two dee stems is supported in a gimbal arrangement in a cylindrical tank, and the dee voltage is generated by a grounded-grid self-excited oscillator.

---

[1] At Nobel Institute of Physics up to the middle of 1954; now at Atomkraftkonsortiet (AKK Atomic Power Group).

However, the Stockholm cyclotron is characterized also by several unusual features which have proved to be valuable. The most prominent one of these is represented by the dee biasing system involving the use of short-circuiting condensers as electrical terminations of the dee stems. This system was first tried in 1950.

Regarding the mechanical design, some guiding features were rigidity and a maximum of flexibility in the use of the machine.

In addition, it may be mentioned that many of the problems which had to be approached in the design of the Stockholm cyclotron were due to the size of the machine (this being bigger than any other fixed-frequency cyclotron in use at the time of design).

It is worth noting that the radius used in the Stockholm cyclotron for the acceleration of ions to an energy of 11 MeV/nucleon is approximately 35–40 % larger than the exit radius used in 60-inch machines for the production of particles of about the same energy (10–11 MeV/nucleon). Consequently, the change in orbit radius per turn at a given energy and a given dee voltage is also greater in the Stockholm cyclotron than in a 60-inch machine. This has certain advantages, for instance in connection with the extraction of the beam. As seen from the data specified above, the magnetic induction used for deuteron acceleration is only somewhat more than half the maximum attainable induction. This state of things has been taken advantage of in the acceleration of heavy ions [4].

The design of the cyclotron was started in the spring of 1946. The initial testing [1] with a deuteron beam at a relatively small radius (48 cm) was performed in the summer of 1950. The first beam at full radius (90 cm) was obtained in July, 1951, after the short-circuiting condenser arrangement still in use had been installed in May of the same year. The nominal deuteron energy at the 90-cm radius was at this time 21 MeV. The design energy for deuterons was 25 MeV and a deuteron beam of this energy was realized at the end of 1951. In the spring of 1955 the cyclotron was adjusted to produce about 11 MeV/nucleon for reasons connected with the work on heavy ion acceleration [4].

After the initial stage of performance had been reached, a period of completion followed. Iron-ore concrete shields were installed in 1952 and the vacuum system was completed with some large and essential components at the end of 1954. In recent years, various improvements have been made. New equipment (e.g., new control equipment for the ion source power supply and a new voltage supply for the dee biasing system) has been designed and constructed.

Work on acceleration of heavy ions was started in the beginning of 1953 [5]. Since then much time and effort have been devoted to the development of equipment necessary for this work (such as ion source arrangements, probe mechanism and different types of probes). This equipment is described elsewhere [4].

In March 1958, the cyclotron was shut down and taken to pieces for remodeling. Up to this date it was run exclusively with internal beams. However, when the dees were designed [7], provisions were made for mounting an internal dc deflector in one of them and the construction of components for a deflector system was started several years ago. During the remodeling period the work on the deflector arrangement has been continued. At the time of writing the deflector is being installed in connection with the reassembling of the dee system.

2. Building

To get a satisfactory radiation shield between the cyclotron and the surroundings the machine has been placed in an underground hall (Fig. 1). This hall which is resting directly on rock is surrounded on all sides by rock, clay and earth. On the top it is shielded by a water pond two metres deep. The control room (Figs. 1 and 14) is housed in a three-story building above ground. The connection between this building and the cyclotron hall is via a stairway or an elevator to the bottom of a shaft from which a corridor leads to the hall. A removable 150-cm thick wall of iron-ore concrete partly closes the corridor, leaving an opening 140 cm broad. This opening can be closed by a door also made of iron-ore concrete and weighing 35 tons. The door is electric-motor driven and can be moved along tracks traversing the corridor.

In the three-story building and its basement several rooms are used for housing auxiliary equipment for the cyclotron (such as rectifier for the radio-frequency generator, electric switch-board, dc generators and heat exchangers).

The ventilating system is so arranged that the air pressure in the cyclotron hall can be kept somewhat below the pressure in the surroundings in order to prevent radioactive gases or dust from moving out from the hall.

For quick transport of radioactive samples from the cyclotron to the radiochemical laboratory (which is also housed in the building above ground) a pneumatic dispatch system can be used.

An interior view of the cyclotron hall is shown in Fig. 7.

3. Magnet

The basic design of the magnet was made by Dr. L. Dreyfus of the ASEA Co. which carried out the construction. The design was made according to specifications of the Institute. Among other requirements that for a large experimental space around the acceleration chamber had to be met. The vertical parts of the magnet yoke had to be beveled (compare Fig. 5) so as to give the space necessary for turning the chamber and the dee stem tanks through about 30° to either side.

The construction of the magnet is shown in Fig. 2. The yoke is composed mainly of 12 big blocks. These have been built up by welding together 30-mm thick steel plates and have weights from 25 to 30 tons each. Each of the two poles is a solid forging weighing 18 tons.

The coils have been wound with 25×28 mm^2 copper bars with a central channel (11 mm in diameter) for water cooling. Each coil consists of 7 flat coils, each of these having two layers of windings. These two-layer coils are connected in series electrically and in parallel for the cooling water. The total number of turns of the magnet windings is 504. The complete magnet has a weight of 400 tons, the copper windings weighing 27 tons.

The poles of the magnet are 225 cm in diameter at the faces. They are extended by the 125-mm thick pole tips which are incorporated in the acceleration chamber. These plates are tapered and have a smallest diameter of 211 cm. Without the shims used for correcting the magnetic field the total gap between the pole faces is 350 mm; the distance between the pole tip plates is 330 mm and the gap on each side of the chamber is 10 mm.

The rim around the lower pole is used for fixing the acceleration chamber to the

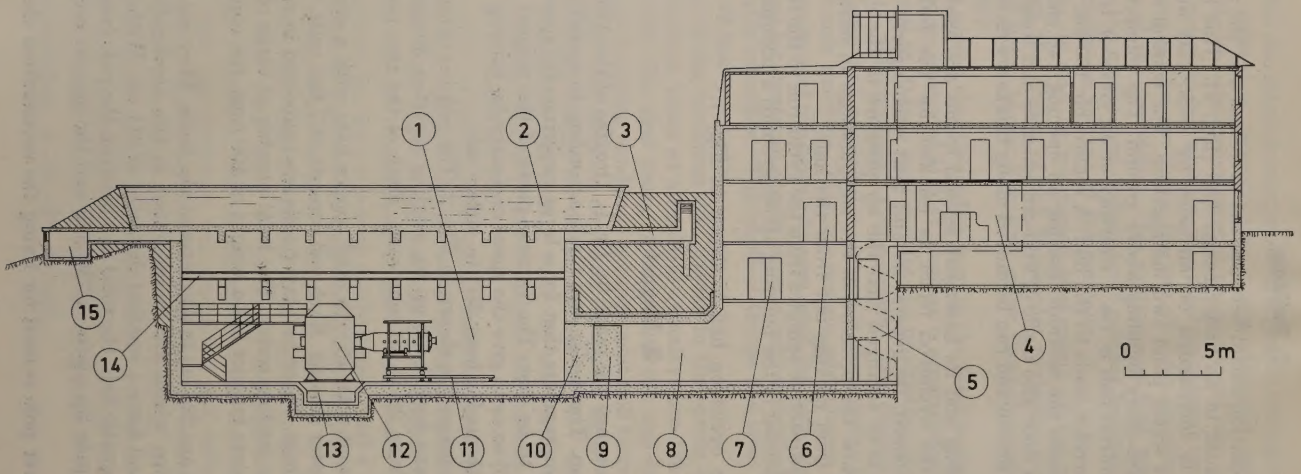

Fig. 1. Longitudinal section through the cyclotron hall and the adjacent building. (This sectional view is, in fact, a juxtaposition of several sections in different vertical planes.) 1 cyclotron hall. 2 water pond. 3 air intake. 4 control room. 5 communication shaft (stairway and elevator). 6 to high-voltage rectifier room. 7 to motor-generator room and heat-exchanger room. 8 corridor. 9 iron-ore concrete door. 10 removable iron-ore concrete wall (partially closing the corridor). 11 track for cyclotron carriage. 12 cyclotron magnet. 13 pit housing auxiliary equipment (below the magnet). 14 track for 30-ton crane. 15 fan room.

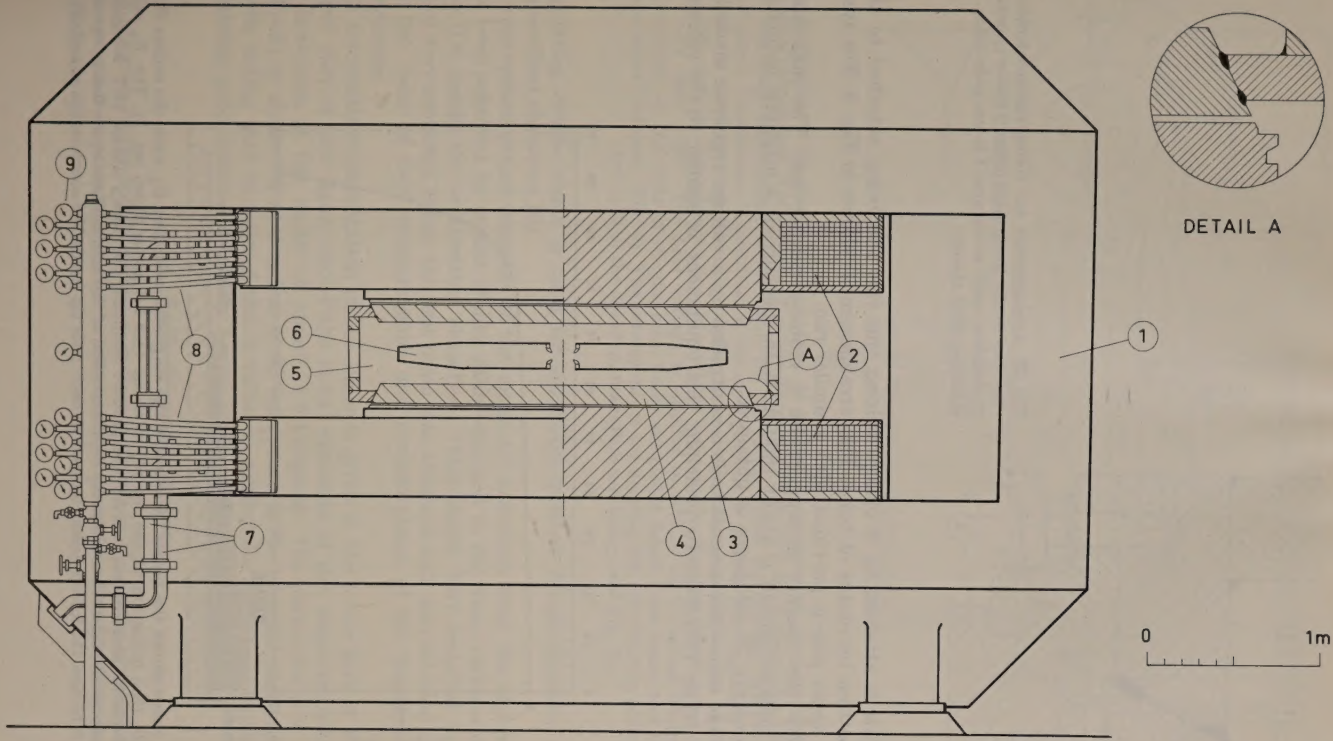

Fig. 2. View of the magnet with the acceleration chamber in the pole gap. (This view is from the north side; the dee stems are on the opposite side; compare Fig. 5.) 1 magnet yoke. 2 coils. 3 lower pole piece. 4 lower pole tip. 5 acceleration chamber. 6 dee (schematically). 7 current leads. 8 water connections (rubber tubing). 9 pressure gauges with electrical contacts.

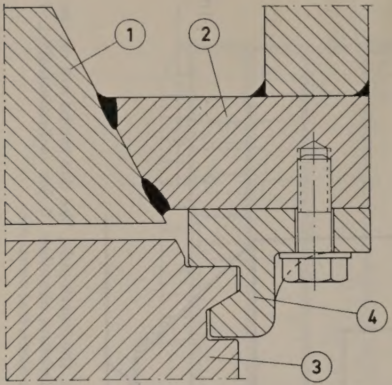

Fig. 3. Arrangement for fixing the acceleration chamber to the lower pole piece. 1 lower pole tip. 2 stainless steel structure. 3 lower pole piece. 4 stainless steel clamp.

magnet. This is attained by 8 clamps seizing this rim and being attached to the chamber bottom by means of bolts. This arrangement is shown in Fig. 3. For symmetry the upper pole is provided with a similar rim.

Power for the magnet is supplied by a motor-generator set. The maximum attainable magnet current is about 1500 A. With this current a magnetic induction of approximately 20 kilogauss is obtained.

The voltage across the magnet coils is controlled by a voltage regulator made by ASEA Co. (type YRLBE). In principle, this equipment is similar to the voltage-

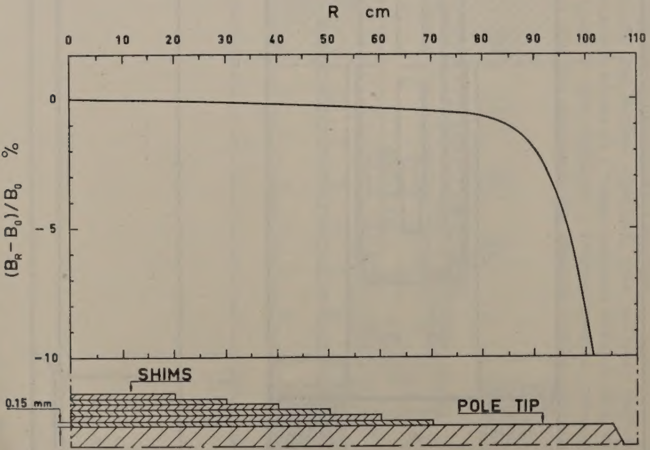

Fig. 4. The curve shows the radial variation of the magnetic induction B_R with the radius R for a value of B_0 (the induction at the centre) of about 11.6 kilogauss (from ref. 7). The B_0 value used for deuteron acceleration is with the present oscillator frequency about 10.7 kilogauss. The lower part of the figure is a schematic representation of the shims (there is one flat-pyramidal pile of 0.15-mm thick iron disks clamped to each pole tip inside the acceleration chamber).

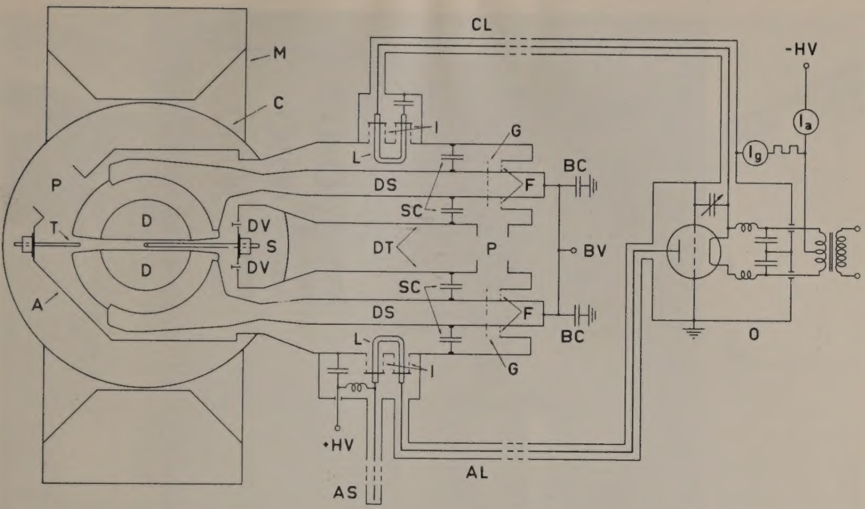

Fig. 5. Schematic diagram of the cyclotron. M magnet. C magnet coil. A acceleration chamber. P pump connections. S ion source. T probe (target). D dees. DV dee voltage pick-up electrodes. DT dee stem tanks (outer conductors). DS dee stems (inner conductors). SC short-circuiting condensers. I insulators. G positions of dee stem gimbals. F flexible and insulating seals (rubber rings). BC blocking condensers. L coupling loops. AL anode transmission line. AS anode stub line. CL cathode transmission line. O oscillator cabinet. The high-voltage rectifier is connected at +HV and −HV. The bias voltage is applied to BV. — In the actual design the pump connections at the ends of the dee stem tanks are placed below these tanks and the coupling loops above (compare Fig. 8). The arrangements for keeping the dee stems in position (outside the ends of the dee stem tanks) are not shown (see Fig. 8).

regulating device which is used for the Nobel Institute 80-cm cyclotron and which is described elsewhere [6].

Appropriate radial decrease of the magnetic induction from the centre outward has been achieved by means of disk shims clamped to the inner surfaces of the pole tips (i.e. inside the acceleration chamber). These shims were installed in 1949 [7]. They were mounted before the first beam was obtained and were selected exclusively on the basis of field measurements and considerations of the magnetic focusing conditions.

A schematic representation of the shims is given in the lower part of Fig. 4. The upper part of this figure shows the radial variation of the magnetic induction for an induction at the centre of about 11.6 kilogauss. The parameter $n = -(R/B) \times (dB/dR)$ is about 0.3 at a radius of 90 cm (which is the nominal exit radius). It is worth noting that in spite of this n value no difficulties have been experienced in attaining good internal deuteron beams at the radius mentioned.

4. Radio-frequency system

A diagram of the radio-frequency system is shown in Fig. 5. As already mentioned, this system is in principle similar to that used to operate the Crocker 60-inch cyclotron at Berkeley [8].

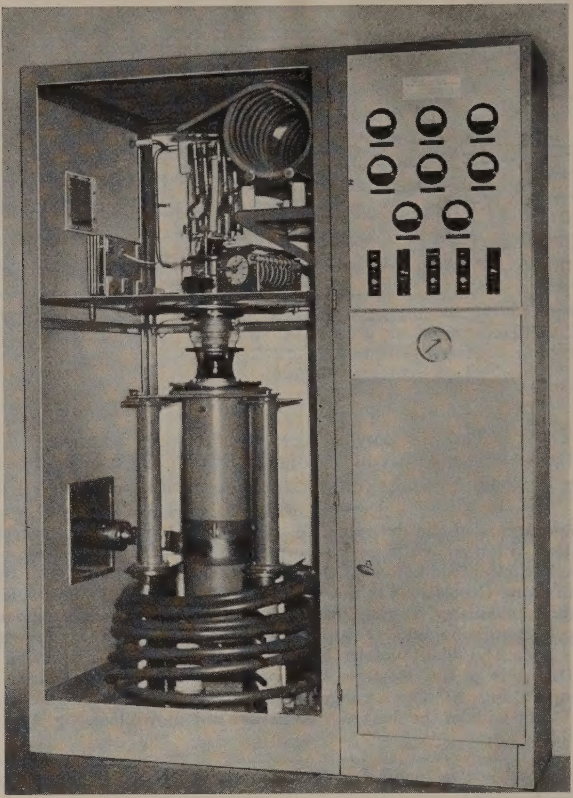

Fig. 6. Photograph of the oscillator cabinet with the water cooled tube in its water jacket and the control panel to the right (compare Fig. 7).

This circuit arrangement has the following main features:

1. The generator is a grounded-grid self-excited oscillator.
2. The dee system is the only frequency determining circuit.
3. The frequency determining system has big dimensions and as a consequence a high value of the quality factor Q and fairly low losses.
4. The voltages and currents on the transmission lines form standing waves. The correct mode of oscillation is obtained by making the electrical length of the plate line slightly shorter than a quarter wave and the cathode line in electrical length a little longer than a quarter wavelength.

The oscillator uses a single water- and forced-air-cooled tube (Standard Telephones and Cables, Ltd., London, Type 3Q/331E). It permits a maximum anode dissipation of 160 kW. A three-phase full-wave high-voltage rectifier (built by ASEA) which has a maximum output of 400 kW at 20 kV supplies power to the oscillator.

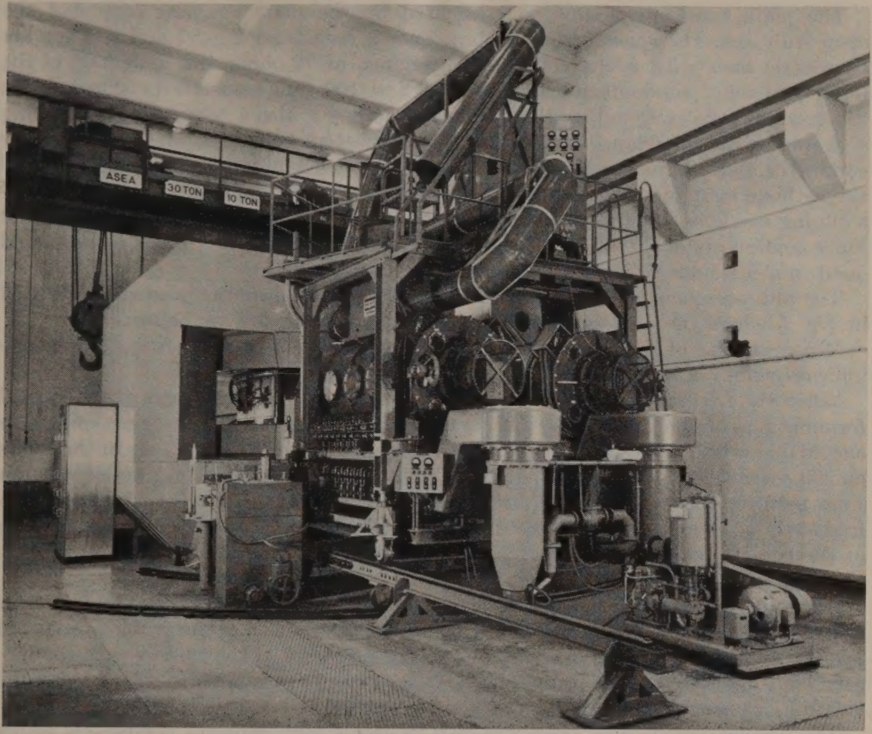

Fig. 7. Photograph of the cyclotron showing the magnet, the dee stem tanks with their vacuum pumps and the oscillator on the gallery. The anode transmission line and the anode stub line are also visible.

Fig. 6 gives an indication of how the oscillator is arranged with the water-cooled tube in a shielding cabinet. This cabinet is placed on a gallery above the dee stem tanks as shown in Fig. 7.

The dimensions and shape of the dees were determined in consideration of the space necessary for the beam profile and for the deflector arrangement [7].

As indicated in Fig. 5 the inner conductor of each dee line has a constricted part adjacent to the dee. The shape of this part has been given by the space available between the magnet coils and at the entrance of the acceleration chamber. The design chosen for the dee line has been considered to be suitable from a radio-frequency point of view. It involves the use of an elliptical cone line between the dee and the cylindrical part of the dee line. This construction has been studied both by numerical calculations and by model experiments [9].

In general, a basic construction principle has been to make the dimensions such that the radio-frequency losses will be equally divided by the dees, the elliptical cone line and the cylindrical part of the dee line. This seems to represent a reasonable compromise taking into account both radio-frequency losses and construction costs.

The plate transmission line is terminated by the plate coupling loop and the open stub line. The construction of these lines is seen from Figs. 7 and 8. They are concentric lines with a characteristic impedance of 72 ohms, the diameters of the outer and inner conductors being 330 mm and 100 mm respectively. The lengths of these lines are easily adjustable. The cathode line is also a concentric line having a characteristic impedance of 72 ohms, the diameters being 165 mm for the outer conductor and 50 mm for the inner conductor. It is terminated at the tank end by the cathode coupling loop and a capacitor. Its electrical length can be adjusted by a tuning condenser at the cathode of the tube. The spacers between the outer and inner conductors of the lines are made of Mycalex. The coupling loops (constructed of 61-mm diameter copper tubing) are water cooled.

The radio-frequency voltages on the dees are measured at the positions indicated in Fig. 5 where the pick-up electrodes used for this purpose are shown.

Measurements of the *Q*-value for the dee-line system by a radio-frequency bridge indicate values of roughly 20,000.

When the first tests of the radio-frequency system were performed, the electrical terminations of the dee stems consisted of conventional short-circuiting spiders in accordance with the original design. This system was first tried with air in the tanks and was found to work as anticipated. As soon as tests with the tanks under vacuum were performed, however, the system started to oscillate in a wrong mode with a frequency about twice the design frequency. This was caused by electron loading of the dees [1] due to the phenomenon now sometimes called "multipactoring" (see, e.g., ref. 10 and 11).

Attempts to overcome the difficulties in the usual way by means of a small booster oscillator [1] did not give satisfying results. The final solution of the problem involved insulation of the dee stems from ground and replacement of the spiders with condensers. This made it possible to apply a dc bias voltage to the dees to sweep away the electrons causing the above-mentioned phenomenon.

The problem which now arose was how to design high-capacity condensers which would be able to withstand the very high radio-frequency currents (several thousand amperes) flowing at the voltage node of the dee lines. The mechanical construction of the condensers made for this purpose is described in Section 5.

The dc bias voltage applied to the dees has usually been −700 volts. It is supplied by a mercury valve rectifier having a maximum output of about 5 kV.

The measured peak value of the dee-to-dee voltage has usually been in the range 150–200 kV. Under no-load conditions, the last-mentioned potential is obtained with an oscillator power input of about 130 kW. As the dee voltage is measured near the dee neck (see Fig. 5) it is to be expected that the voltage at the centre of the dee gap is somewhat higher than the measured value (about 15 % higher according to the model experiments described in ref. 9).

5. Mechanical construction of some components of the tank system and the dee line system

Chamber and dee stem tanks

The main parts of the vacuum envelope are the acceleration chamber and the two dee stem tanks (Figs. 5 and 8). The chamber has been described in detail elsewhere [7]. It consists of an all-welded structure, the tapered pole tips being welded into a framework of non-magnetic stainless steel (compare Fig. 2).

Fig. 8.

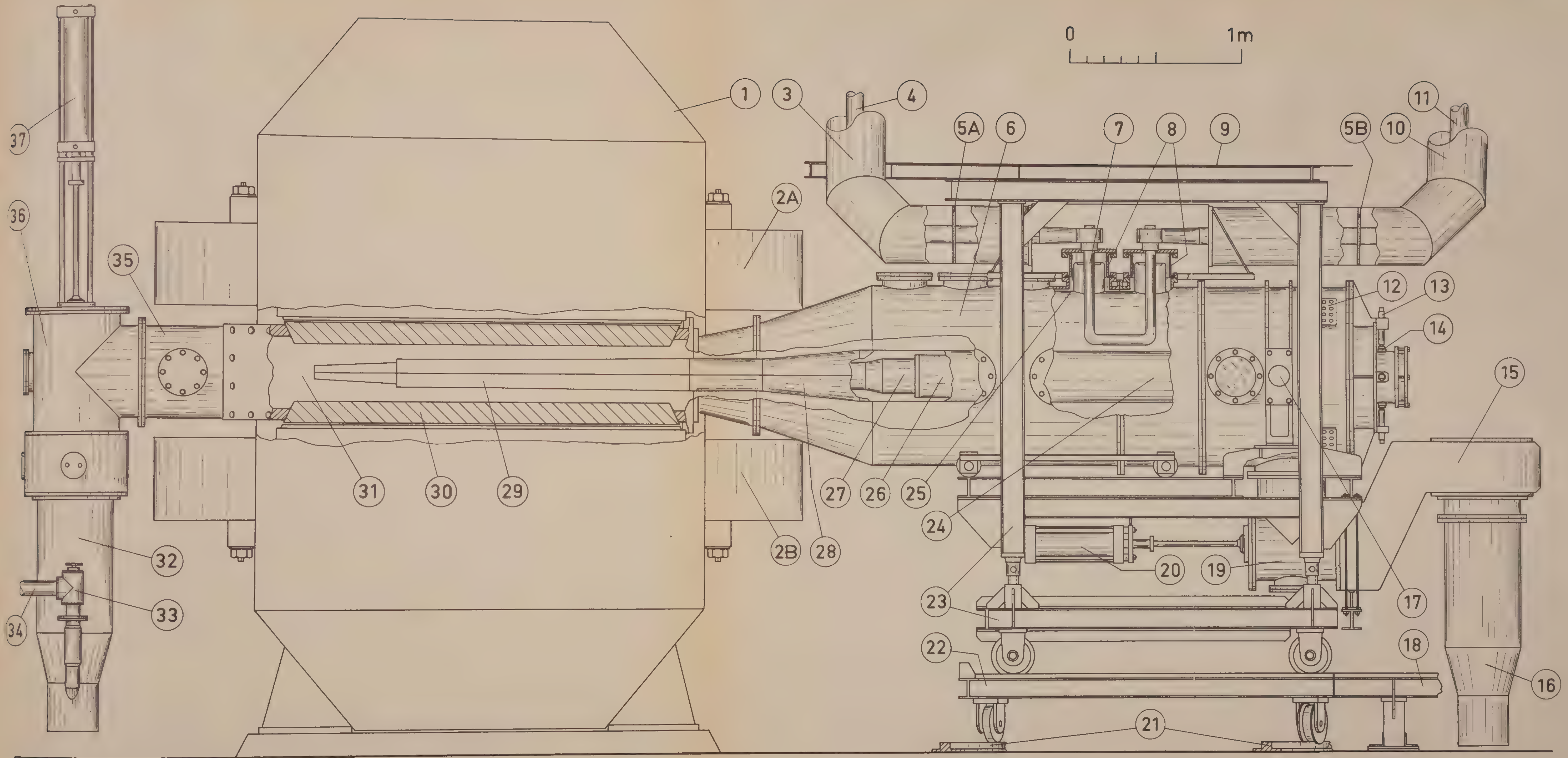

Fig. 8. Simplified elevation drawing of the cyclotron. Several components have been omitted for clarity. 1 magnet yoke. 2 A, 2 B magnet coils. 3, 4 outer and inner conductors of anode stub line. 5 A, 5 B Mycalex insulators. 6 dee stem tank. 7 anode coupling loop. 8 quartz insulators. 9 gallery. 10, 11 outer and inner conductors of anode transmission line. 12 entrance for cooling pipes. 13 dee stem positioning screw (four around each dee stem). 14 fibre insulator. 15 pump duct. 16 diffusion pump; the refrigerated baffle is mounted between the pump and the duct. 17 position of dee stem gimbal (compare Fig. 10). 18 track for tank carriage. 19 vacuum valve. 20 pneumatic cylinder. 21 tracks bent to a circular shape. 22 trolley. 23 tank carriage. 24 dee stem shell. 25 dee stem tank liner. 26 rear part of dee supporting shaft. 27 front part of dee supporting shaft. 28 cone line section of dee stem shell. 29 dee. 30 lower pole tip. 31 acceleration chamber (simplified representation; the liners and shims are not shown). 32 diffusion pump. 33 vacuum valve. 34 to backing pump. 35 pump duct (connected to the chamber at the position shown in Fig. 5). 36 vacuum valve. 37 pneumatic cylinder.

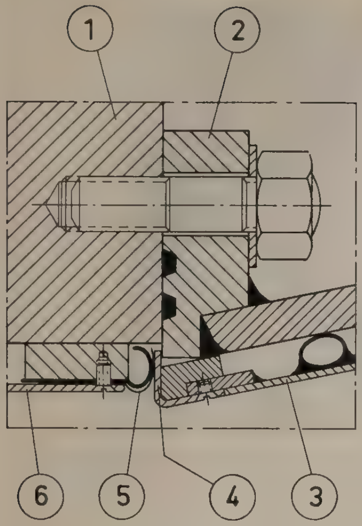

Fig. 9. Contact arrangement. 1 acceleration chamber. 2 dee port cover plate. 3 dee stem tank liner. 4 copper flange. 5 spring loaded copper foil. 6 chamber liner.

Each dee stem tank consists of three sections as shown in Fig. 8. The section nearest to the magnet is made of non-magnetic stainless steel; the other sections are made of ordinary steel. The internal diameter of the cylindrical parts of the dee stem tanks is 103 cm; the wall thickness is 12 mm. Connection between the dee stem tanks and the acceleration chamber is via two short tubes extending from the dee port cover plate. These parts of the tank system are also made of non-magnetic stainless steel.

The inner surfaces of the chamber structure and the dee stem tanks are covered with 2-mm thick copper liners serving as radio-frequency conductors. The liner of each of the dee stem tanks is of one-piece construction. All liners are water-cooled having copper pipes soldered to the side facing the steel envelope. Reliable electric contact between the dee stem tank liner and the chamber liner is obtained by an arrangement shown in Fig. 9.

Dees and dee stems

A detailed description of the mechanical construction of the dees has been given in a previous paper [7]. The height of the space available to the beam is about 12 cm at the central part of the dees. From a radius of 60 cm to the outer radius of 95 cm the dees are tapered, the free height at the 95-cm radius being about 5 cm.

Each dee has internally a supporting aluminium frame which is bolted to the rectangular end plate of a steel shaft inside the dee stem shell. This steel shaft consists of two parts (Fig. 8). The part adjoining the dee is made of non-magnetic stainless steel; the rear part is a tube of ordinary steel about 245 mm in outer diameter and with a wall thickness of about 22 mm.

At the position indicated in Figs. 5 and 8 the steel shaft is suspended in a gimbal arrangement (Fig. 10). As the dees are biased the dee stems must be electrically insulated from the dee stem tanks. For this purpose the two horizontal shafts by

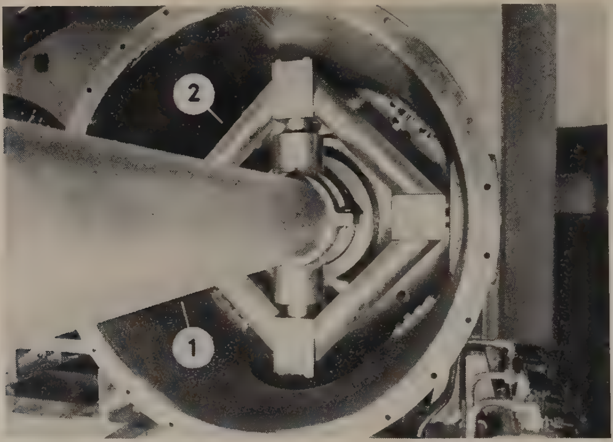

Fig. 10. Dee stem gimbal arrangement. 1 dee stem (steel shaft). 2 gimbal.

means of which each gimbal is suspended from the surrounding tank are insulated from the tank wall by use of Mycalex and mica. Behind the gimbal the steel shaft projects from the dee stem tank through a thick rubber ring as indicated in Fig. 5. Outside the tank the steel shaft is kept in position by four screws which also serve the purpose of adjusting the dee stem position. The rubber ring provides vacuum tightness, adequate flexibility for positioning the stem and also a sufficient insulation for the bias voltage.

The dee stem shell is made of copper and built up of two sections (Figs. 5 and 8). The rear part is a circular tube; the shell between this tube and the dee shell is the cone line section mentioned above. This section is split longitudinally. The joints between the different parts of the shells are made by means of monel screws. Cooling water for the dees and the dee stem shells is circulated through water lines inside the copper structure.

Short-circuiting condensers

As already mentioned, the first attempts to apply a dc bias to the dees of the Stockholm 225-cm cyclotron in order to prevent discharges in the acceleration chamber were made in 1950. The short-circuiting system initially tried consisted of water-cooled mica condensers (the condenser set for each dee stem having a capacity of about 40,000 micro-microfarads). However, troubles shortly occurred with these condensers. They broke down at a fairly low radio-frequency voltage in vacuum despite the fact that they could stand as much as 4 kV in air. It was not possible to ascertain whether this was due to local heating caused by the high radio-frequency currents or to some other effect, for example, outgassing from the mica sheets. The next step was to try commercial Mycalex condensers, but this attempt failed too for the same reasons as in the previous case.

The short-circuiting arrangement installed in 1951, and still in use, consists of six water-cooled plate condensers around each dee stem, giving about 40,000 micro-

microfarads from stem to ground. A brief description of these condensers is given below.

Each condenser is built as shown in Figs. 11 and 12. The condenser plates which are about 2 mm apart are made of aluminium, the thickness of these being 4 mm for the two outer plates on each side and 2 mm for the intermediate plates. Each plate set is clamped at one end together with spacers of flat copper bars. The two sets are held together by means of two 8-mm thick Mycalex plates, one on each side of the condenser. The free ends of the aluminium blades are stabilized by supports from the Mycalex plates.

The outer plate set, which is connected to the copper liner of the dee stem tank, is clamped between brass bars to which cooling pipes have been silver soldered. The inner plate set is clamped between a water-cooled brass ring which holds together all six condensers around the dee stem, and a water-cooled brass bar. Cooling of the condenser plates is achieved by conduction to the clamping bars and to the carrier ring. To provide as good contact as possible between the plates the copper spacer bars have been ground.

Electric contact to the dee stem is made by means of contact fingers of copper on each side of the inner plate set. These fingers are clamped to the dee stem liner with clamping rings of copper, the one on the front side (facing the dees) being water-cooled. In a similar way, contact between the outer condenser set and the outer copper liner is provided by means of copper fingers extending forward from the rear side of the condenser. Also for this purpose a water-cooled clamping ring is used. A photograph of the condensers on one of the dee stems is shown in Fig. 13.

The weight of the six condensers around each dee stem is about 200 kg. To facilitate the movement of this heavy condenser set for tuning purposes, the carrier ring is resting on two needle bearings which can roll along the cylindrical part of the dee stem liner. It may be mentioned that this liner which consists of a copper tube with a 3-mm thick wall is rigid enough for carrying the condensers without appreciable deformation.

Carriage arrangement

The dee stem tanks are mounted on a four-wheeled carriage (Figs. 7 and 8) on top of which is a gallery for carrying the oscillator and auxiliary equipment. For pulling the dees out of the chamber the dee stem tank system is disconnected from the chamber by unbolting the dee port cover plate. The dees are pulled out by rolling the carriage backwards on two tracks. As the oscillator and the transmission lines are fixed to the carriage they ride along with the dee stem tanks.

As can be seen from Fig. 8 the front parts of the tracks on which the carriage can be rolled are mounted on a four-wheeled trolley resting on tracks running in circular arcs. The centres of these arcs coincide with the centre of the magnet. This arrangement has the purpose of facilitating lateral changes in the position of the tank system. For the same purpose, the chamber can be turned around the vertical axis of the magnet by means of three bogies resting on a track supported by the lower pole.

6. Vacuum system

If reasonably steady operation of a fixed-frequency cyclotron of the size concerned in this paper is to be achieved, the vacuum system must be designed to meet the following two requirements:

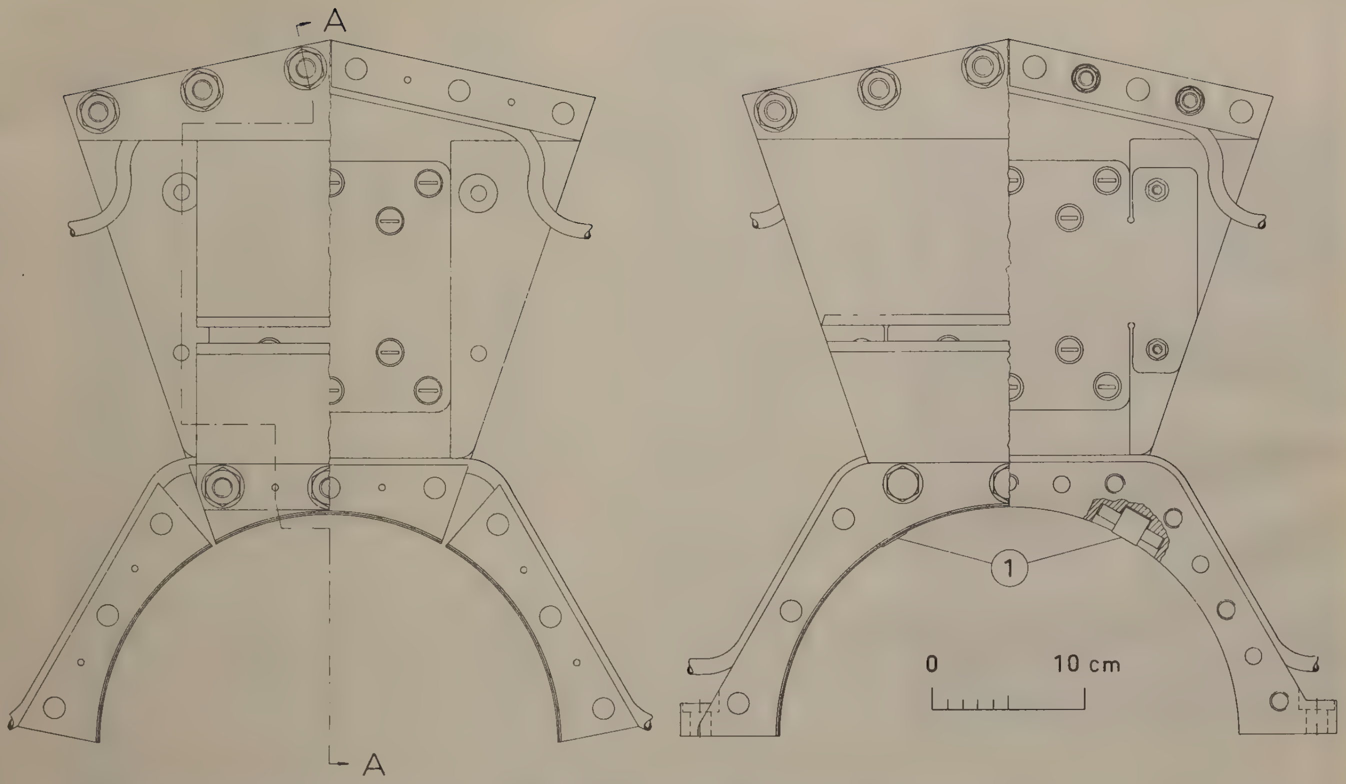

Fig. 11. Short-circuiting condenser. Section A—A is shown in Fig. 12. There are six condensers around each dee stem. The carrier ring consists of two halves; the figure shows the upper half with two needle bearings at 1.

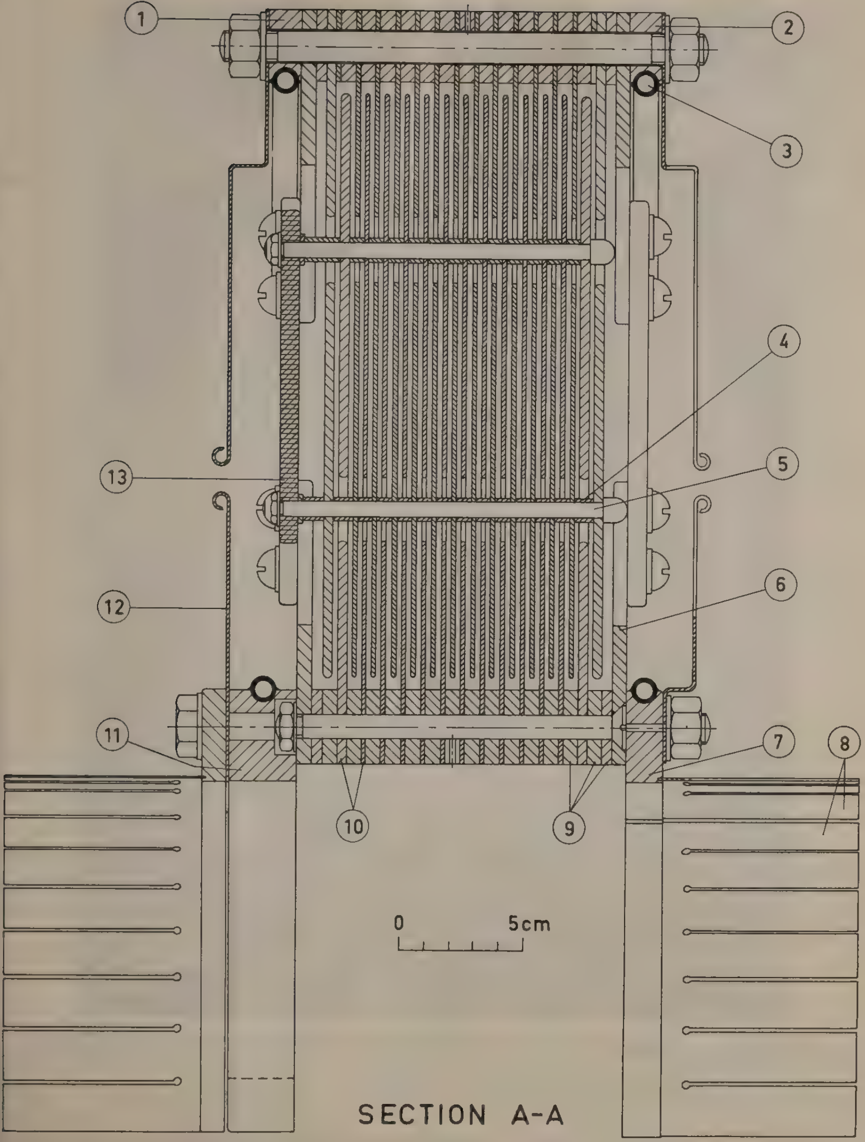

Fig. 12. Cross section of one of the short-circuiting condensers (see Fig. 11). 1, 2 clamping bars (brass). 3 cooling pipe. 4 cylindrical spacer (copper). 5 supporting rod (copper). 6 aluminium plate. 7 clamping bar (brass). 8 contact fingers (copper). 9 copper spacers. 10 aluminium plates. 11 carrier ring. 12 copper shield. 13 Mycalex insulator (one on each side).

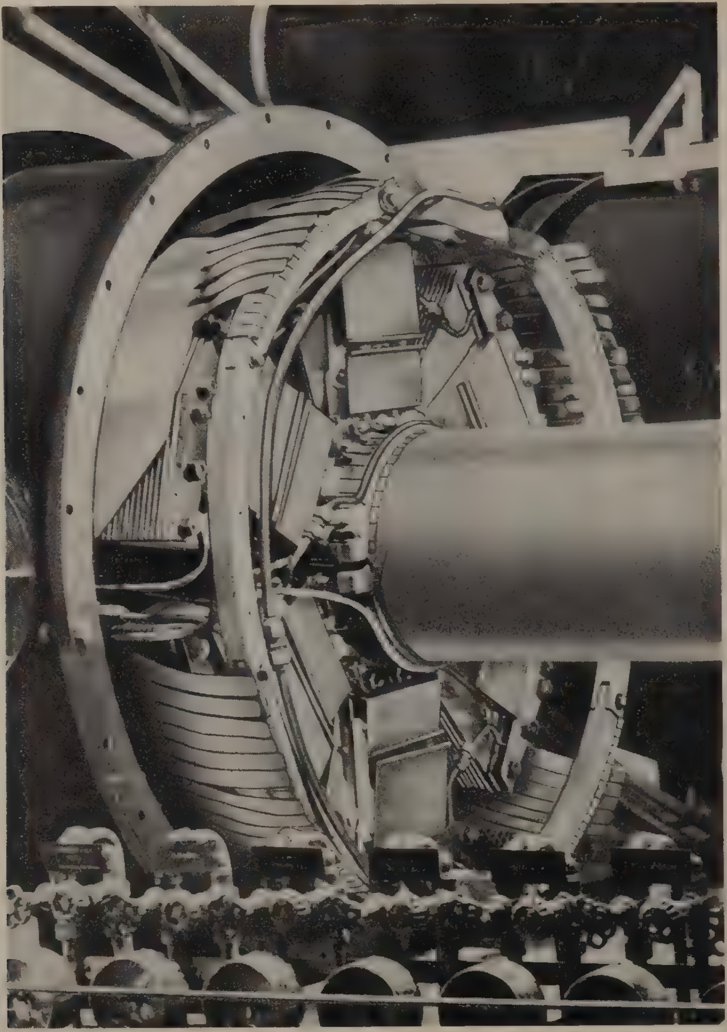

Fig. 13. Photograph of the six condensers around the east dee stem. The inner and outer clamping rings are visible.

1. The vacuum maintained in the tank system with no gas in the ion source must be better than 10^{-5} mm Hg.

2. The pumps must have a pumping speed high enough for handling not only the gas flowing through the ion source but also the large quantities of gas which may be released from the big surfaces by, for instance, electric discharges.

These considerations were kept in mind when the design of the vacuum system described below was worked out.

The total volume of the acceleration chamber and the dee line tanks is about 7,000 litres. For the evacuation of this system three oil diffusion pumps (National Research Corporation, H 16) are used. One pump is connected to each end of the dee line tanks and one to the acceleration chamber (see Figs. 5, 7 and 8). The unbaffled pumping speed of each pump is about 4,000 litres per second at a pressure of 10^{-5} mm Hg.

As backing pumps, two Kinney pumps (DVD 8810) are used (the two diffusion pumps at the ends of the dee stem tanks having one in common).

Oil migration from the diffusion pumps into the vacuum system is prevented by freon-refrigerated baffles, one on top of each pump. The baffle temperature is usually kept at −20°C to −30°C. The reduction of the nominal pumping speed by these baffles is estimated to be less than 50 %. Each of the three diffusion pump ducts is provided with a pneumatically operated valve (see Fig. 8). These valves are actuated by the interlock system provided for safety of the vacuum equipment.

Mainly two types of rubber gaskets are used as vacuum seals. Most of the static seals are gaskets of a square cross section (5×5 mm^2) in grooves of types described elsewhere [7]. With few exceptions rotating or sliding components and small flange connections are sealed by means of O-ring gaskets.

Connection between copper pipes inside the vacuum system has to a large extent been made by means of a commercially available gasketless screw connection. In this case the flanged ends of the two copper pipes to be joined are pressed against the conical ends of a brass adapter. Some 90 joints in the water lines inside the vacuum tanks have been made in this way and used for many years without any trouble.

The flange and groove dimensions have been standardized as far as possible to facilitate design and construction and also stock-keeping of gaskets.

The pressure on the high-vacuum side of the system is usually measured by an ionization gauge (tube type 3S31-B, made by Standard Radio och Telefon AB). This gauge is connected to the front part of one of the dee stem tanks. Mainly for checking purposes, a Philips ionization gauge (Consolidated Vacuum Corporation, PHG-09) is used.

After the system has been well outgassed and with no gas in the ion source the tank pressure is about 2×10^{-6} mm Hg. The operating pressure when accelerating deuterons is approximately 5×10^{-6} mm Hg. When accelerating 6-charged heavy ions [4] the machine is run at still higher pressure (usually 1 to 3×10^{-5} mm Hg).

7. Ion source. Probe arrangements

For the first years the cyclotron was run with a hooded arc ion source similar to that described by Cowie and Ksanda [12]. This source was capable of producing sufficient internal beams of protons and deuterons (deuteron currents of 200 μA were easily obtained at full radius).

Shortly after the work on heavy-ion acceleration was started, some modifications of the ion source were made. These were mainly removal of the ion source hood and addition of a second cone placed above the ion source. The second cone houses an insulated anticathode for reflection of the primary electrons. This arrangement is described in ref. 4.

The ion source filament (a U-shaped wolfram wire, 2.5 mm in diameter) is heated with direct current supplied by a selenium rectifier. This has a maximum output of 5 volts and 500 amperes. Power for the arc is supplied by a dc generator (giving maximum 1 kV and 5 amperes).

The dees are provided with demountable feelers [7]. The feeler arrangement used so far is indicated in Fig. 2. As seen from this figure both dees have feelers of the same shape. The feelers are made of copper and are water cooled.

For bombardment of targets with the intense internal beams of protons, deuterons or alpha particles several types of probes have been constructed. All of these have, of course, been designed to meet the requirements for as efficient cooling as possible.

Whenever possible metallic targets are soldered to the probe. In some cases metallic targets are prepared by melting the target material onto the probe end.

The probes are made of copper and are water cooled. The beam current is measured by measuring the flow rate and the temperature increase of the cooling water. A thermocouple arrangement is used for the temperature mesaurements. The position of the probe is indicated in Fig. 5.

In order to improve the heat transfer from the target surface a shaking device similar to that described by Livingston [13] has been constructed. With this arrangement the target can be moved up and down in the beam at a few oscillations per second.

8. Cooling system

Extensive water cooling is necessary for most parts of the cyclotron. To avoid deposit and corrosion in the cooling pipes distilled water is used. This water is circulated by means of centrifugal pumps in closed systems and is in turn cooled in heat exchangers. There are two such cooling systems with separate heat exchangers. One system provides cooling only for the magnet; the other system cools the oscillator tube and other water-cooled parts of the machine. Cooling of the heat exchangers is effected by means of water from the pond above the roof of the cyclotron hall. If necessary, city water can be used for cooling the heat exchangers. The heat generated in the magnet coils can be used for heating the laboratory premises. For this purpose the cooling water from the magnet is conducted through a heat exchanger connected up with the central-heating system in the Institute.

The flow of water in the cooling system for the magnet is about 90 l/min at a pressure of 10 kg/cm^2. In the other system the flow is about 320 l/min at a pressure of approximately 4 kg/cm^2.

City water available in the cyclotron hall can be used for cooling of such parts of the machine which need a somewhat lower inlet temperature than can be attained for the circulating water. A few parts of the equipment are air cooled.

9. Control system

The electric power for the control system is supplied by a 24-volt storage battery. For reasons of cost almost all electrical connections between the control room and the cyclotron hall have been made with telephone cables. For the same reasons telephone relays are used in the interconnecting safety system.

In principle, the safety system has been designed according to the pattern well-known from most cyclotrons. An extensive arrangement of interlocks is used to protect both equipment and personnel. Some of the safety relays have holding

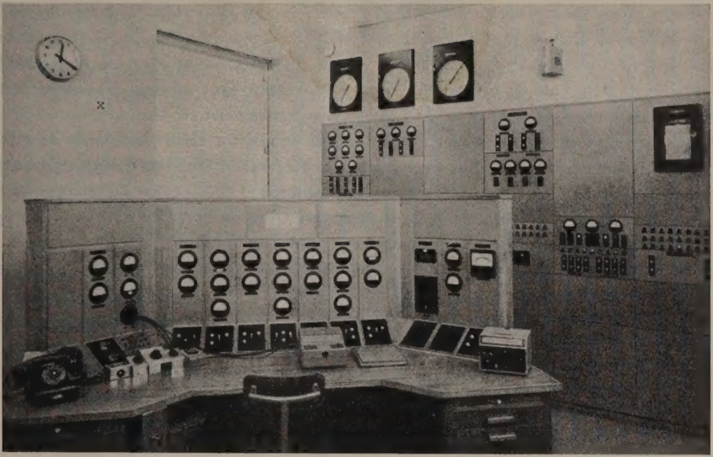

Fig. 14. The cyclotron control room. The control desk and part of the panels are shown.

windings. If a circuit has been switched off by such a relay this has to be reset by the operator before the circuit can be switched on again.

Meters and controls for the various units of the cyclotron are available on panels in the control room (Fig. 14). The panels are divided into subunits. These are of the plug-in type. It is easy, therefore, to disconnect them for maintenance and changes. Signal lights indicate the states of all interlocks.

The control desk has been provided only with those meters and controls which must be available to the operator during operation.

10. Performance

The 225-cm cyclotron has operated satisfactorily for many years with internal beams of protons, deuterons, alpha particles and various heavy ions (carbon, nitrogen, oxygen and neon ions).

The oscillator-frequency used during the last years is 8.1 Mc/sec. With this frequency the machine accelerates ions to a nominal energy of about 11 MeV/nucleon at a radius of 90 cm. Internal beam currents of approximately 300 μA of 22-MeV deuterons are obtained.

Since the beginning of 1953 the cyclotron has been used to a large extent for heavy-ion acceleration. Details of this work are given in ref. 4.

ACKNOWLEDGEMENTS

We wish to express our gratitude to the Director of the Institute, Professor Manne Siegbahn, for the confidence he has shown in us by assigning us to the work on the project described herein, and for his constant encouragement and support.

We are indebted to our colleague, Docent B. Åström, for his helpful cooperation during the first phases of the work.

Before the design work was started we were priveleged to visit (together with Dr. Åström) several cyclotron laboratories in U.S.A. in order to collect information on fixed-frequency cyclotrons. The help given us in various ways on our visit to the Radiation Laboratory at Berkeley by the late Professor Ernest O. Lawrence and the late Professor Joseph G. Hamilton was of great value to our forthcoming work. Professor M. Stanley Livingston of the Massachusetts Institute of Technology also gave much appreciated help and advice. Valuable information was obtained from members of the staffs of several cyclotrons in U.S.A.

Our thanks are due to many industrial firms and works for their assistance in the project. Mention should be made of the ASEA Co. which was responsible for the design and construction of the magnet, and Avesta Jernverks AB which manufactured the acceleration chamber and some other big components of the vacuum envelope. The agreeable cooperation with several representatives of these and other firms is acknowledged. In particular, our thanks are due to Dr. L. Dreyfus of ASEA for his contribution as regards the design of the magnet and to Mr. E. Ladell of the same company.

Assistance in the mechanical design of some parts of the steel construction was given by Docent S. Kasarnowsky and Mr. C. Bartoli.

We convey our thanks also to all those present and former members of the technical staff of the Institute who have contributed to the work during different phases of the project.

From the very beginning, Mr. S. Egnell has assisted in design, construction and testing. Mr. H. Jardemar and Mr. H. Grawem have rendered service, the former as mechanic and draugthsman, the latter as electrician.

Assistance in the design, construction and testing work was given also by several former members of the cyclotron technical staff, viz., Dr. O. Björklund, then electronic engineer, Messrs. B. Fogelberg, J. Kilter, T. Sandström, R. Skolin, A. Kransell, B. Axelsson and E. Lindholm. Work shop service was rendered for a short period by Mr. A. Bandsholm and in later stages by Mr. S. Nilsson. Mr. A. Jansson helped in welding and assembling work.

During early phases of the construction work, some members of the main work shop staff, in particular Messrs. R. Selén and H. Wallén, assisted.

For several years the operation of the cyclotron has been the responsibility of Mr. H. Rundvall with the assistance of Mr. Å. Karlsson. Mr. A. Seifert has assisted in running the machine and in various other ways.

Nobel Institute of Physics, Stockholm 50.

REFERENCES

1. H. ATTERLING and G. LINDSTRÖM, Arkiv för Fysik *4*, 559 (1952).
2. H. ATTERLING and G. LINDSTRÖM, Nature *169*, 432 (1952).
3. ERNEST O. LAWRENCE, LUIS W. ALVAREZ, WILLIAM M. BROBECK, DONALD COOKSEY, DALE R. CORSON, EDWIN M. MCMILLAN, W. W. SALISBURY, and ROBERT L. THORNTON, Phys. Rev. *56*, 124 (1939).
4. H. ATTERLING, Arkiv för Fysik *15*, 531 (1959).
5. H. ATTERLING, Arkiv för Fysik *7*, 503 (1954), Preliminary note.
6. H. ATTERLING, Kungl. Svenska Vetenskapsakademiens Årsbok 1945 (in English).
7. H. ATTERLING, Arkiv för Fysik *2*, 559 (1951).
8. For a detailed description of the Berkeley 60-inch cyclotron oscillator is referred to J. BACKUS, Rev. Sci. Instr. *22*, 84 (1951).
9. G. LINDSTRÖM, Arkiv för Mat., Astr. o. Fysik *35* A, No. 15 (1948).
10. K. R. MACKENZIE, Rev. Sci. Instr. *22*, 302 (1951).
11. F. H. SCHMIDT, G. W. FARWELL, J. E. HENDERSON, T. J. MORGAN, and J. F. STREIB, Rev. Sci. Instr. *25*, 499 (1954).
12. D. B. COWIE and C. J. KSANDA, Rev. Sci. Instr. *16*, 224 (1945).
13. M. S. LIVINGSTON, J. Appl. Phys. *15*, 2, 128 (1944).

Tryckt den 9 maj 1959

Uppsala 1959. Almqvist & Wiksells Boktryckeri AB